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Winds of change?: Projections of near-surface winds under climate change scenarios

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[1] Changes in near-surface wind speeds due to global climate change may have profound geophysical and societal impacts. However, Global Climate Models (GCMs) are unable to replicate the historically observed magnitude and spatial variability of wind speeds, so we apply a downscaling technique to generate probability distributions of wind speeds at sites in northern Europe for historical periods (1961–1990 and 1982–2000) and two future periods (2046–2065, 2081–2100). Projections for the twenty-first century (C21st) indicate no evidence of substantial evolution relative to the end of the twentieth century (C20th), although there is increased divergence of results from downscaling of different GCMs toward the end of C21st. Predicted changes in the downscaled mean and 90th percentile wind speeds are small ($\leq \pm 15\%$) and are comparable to the current variability manifest in downscaling from different GCMs. **Citation:** Pryor, S. C., J. T. Schoof, and R. J. Barthelmie (2006), Winds of change?: Projections of near-surface winds under climate change scenarios, *Geophys. Res. Lett.*, 33, L11702, doi:10.1029/2006GL026000.

1. Introduction

[2] Emission of climate relevant particles such as sea spray and dust [Latham and Smith, 1990], ocean mixing [Munk and Wyunsch, 1998], structural design codes [Ambrose and Vergun, 1997] and viability of renewable energy technologies (wind energy) [Pryor et al., 2005b] are all critically and non-linearly dependent on the prevailing wind climate and particularly the upper percentiles of the wind speed probability distribution. Hence, changing near-surface wind speeds may act as a positive or negative feedback to global warming and may strongly influence the regional economic costs of, or opportunities afforded by, global climate change.

[3] Our geographic focus is northern Europe and specifically the Scandinavian countries. This region experienced a trend toward increased storminess and wind speeds starting in the 1960s, associated with increased prevalence of positive phase North Atlantic Oscillation, that appears to have been broken in the mid-1990s [Alexandersson et al., 2000; Pryor and Barthelmie, 2003]. There is considerable

uncertainty as to future prospects for increased or decreased storminess in this region in part due to somewhat divergent results from different GCMs and high variability in the present climate [Ulbrich and Christoph, 1999]. The study region also has relatively high penetration of carbon-neutral electricity supplies (http://www.nordicenergy.net/_upl/nordicfinal.pdf). For example, in Denmark over 18% of the annual electricity supply is derived from wind farms [International Energy Agency, 2005]. Hence there is great interest in developing a comprehensive assessment of the regional impact of climate change on renewable energy resources including wind-power.

2. Data

[4] Ten coupled Global Climate Models (GCMs) from the data set for the upcoming 4th Assessment Report of the Intergovernmental Panel on Climate Change that have output available with daily resolution are used here; BCCR-BCM2.0, BCC-CM1, CGCM3.1, CNRM-CM3, ECHAM5/MPI-OM, GFDL-CM2.0, GISS-ModelE20/Russell, IPSL-CM4, MIROC3.2 (medium resolution), and MRI-CGCM2.3.2. These span the range of GCMs available in terms of spatial resolution (coarsest $\sim 4 \times 5^\circ$, finest $\sim 1.875 \times 1.875^\circ$) and model formulations (spectral v. Cartesian). GCM output for two historical periods (1982–2000 and 1961–1990) are taken from climate simulations of the twentieth century. GCM output for 2046–2065 and 2081–2100 are from simulations conducted using the A2 emission scenario which equates to a moderate to high greenhouse gas cumulative emission resulting in global carbon dioxide emissions from industry and energy in 2100 that are almost four times the 1900 value [Nakicenovic and Swart, 2000]. Daily average wind speeds at 10-m for 1982–2000 are drawn from; International Surface Weather Observations (1982–1997) and Integrated Surface Hourly Observations (1995–2002) [Lott et al., 2001], and are supplemented in Figure 1 by mean wind speeds recorded in national inventories from the Scandinavian countries (www.nve.no/vindatlas) [Alexandersson, 2006; Cappelen and Joergensen, 1999; Drebs et al., 2002].

3. Methodology

[5] Coupled GCMs are the primary tools for developing climate projections [Houghton et al., 2001]. However, the resolution of GCMs is low relative to the observed spatial heterogeneity of wind climates (Figure 1a), and there is considerable variability between GCMs (Figure 1b), which is also manifest at the individual grid-cell level (Figure 2). Some of the GCM-to-GCM variability may reflect differences in the vertical interpolation from the lowest model level to 10 m height and/or the temporal averaging applied

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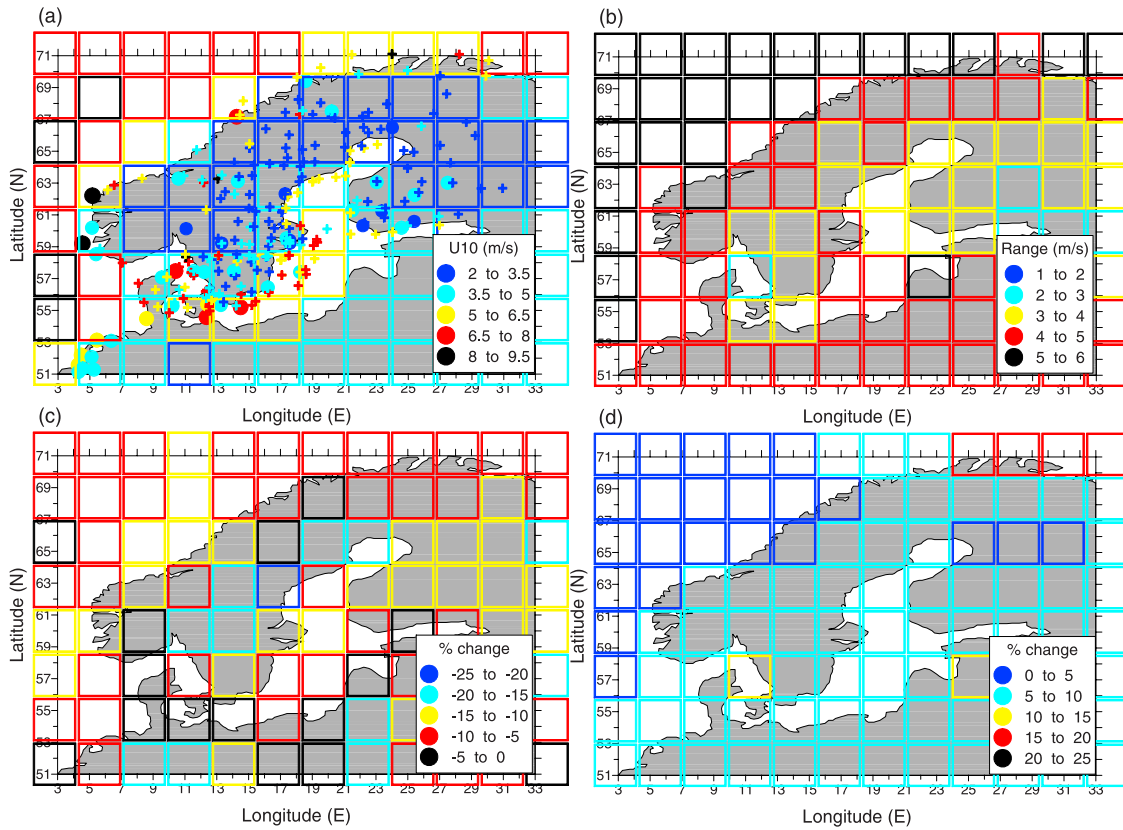


Figure 1. (a) Mean wind speed at 10-m above the surface (U_{10}) as observed during 1982–2000 at 45 surface observing stations used in the downscaling (solid circles) and from national inventories (crosses), and grid-cell average wind speeds from the highest resolution GCM – ECHAM5 (grid-boxes). Note that in all frames the GCM output has been interpolated using inverse-distance squared weighting onto the grid resolution ($2.875^\circ \times 2.875^\circ$) common to five of the ten GCMs used. Note also that the data periods of the national inventories (shown by crosses) differ by country: For Denmark, Sweden and Norway the mean wind speed is from 1961–1990, while for Finland the data period is 1971–2000. (b) Range of mean wind speeds from 1982–2000 as simulated by the ten GCMs. (c and d) Percent change in mean 10-m wind speeds between 1961–1990 and 2081–2100 from the GCM simulations of the A2 emission scenario where Figure 1c shows the maximum percentage decrease ($((2081-2100)-(1961-1990))/(1961-1990)$) exhibited by any of the GCMs and Figure 1d shows the largest increase from any of the GCMs.

(see the IPCC data portal for details of the models <https://esg.llnl.gov:8443/index.jsp>). Nevertheless, the range of GCM predicted mean wind speeds for individual grid cells is up to 6 m s^{-1} in an area where the mean 10-m wind speed is between 2 and 10 m s^{-1} . This, coupled with the inconsistency of climate change signals between the GCMs (Figures 1c and 1d) (the range of grid-cell average percent changes in mean wind speeds between 1961–1990 and 2081–2100 from the different GCMs exceeds 25%), implies a need to downscale more spatially discretized wind speed climates from more robustly simulated parameters from GCMs using either dynamical tools [Pryor *et al.*, 2005a] or empirical methods [Pryor *et al.*, 2005b].

[6] The empirical downscaling technique employed here is focused on developing a probability distribution of wind speeds during a specific time window rather than a time series of wind speeds [Pryor *et al.*, 2005b]. The two-parameter Weibull distribution is used to describe the probability distribution of wind speeds (U):

$$p(U) \equiv \frac{k}{A} \left(\frac{U}{A} \right)^{k-1} \exp \left[- \left(\frac{U}{A} \right)^k \right] \text{ for } U \geq 0, A > 0, k > 0.$$

The parameters are a dimensionless shape parameter (k) which describes the peakedness of the distribution and a scale parameter (A) which is a measure of the central tendency.

[7] The downscaling models of Weibull A and k at each site are developed based on data from the conditioning period which is used to compute 12 values (one for each calendar month) of the predictands (A and k) and each predictor (mean and standard deviation of 500 hPa relative vorticity (ζ) and the mean daily sea-level reduced pressure gradients (PG)) as simulated by the GCMs. The linear regression equation for each site, GCM and each of the two Weibull parameters is thus determined from:

$$A_i = c_1 \cdot \overline{PG_j} + c_2 \cdot \overline{\zeta_j} + c_3 \cdot \sigma(\zeta_j)$$

where i is the station, j is the value of the circulation parameters for the GCM grid-cell containing the station, and $c_{1,2,3}$ are the regression coefficients.

[8] The regression models are developed independently for each of the Weibull parameters from each station using

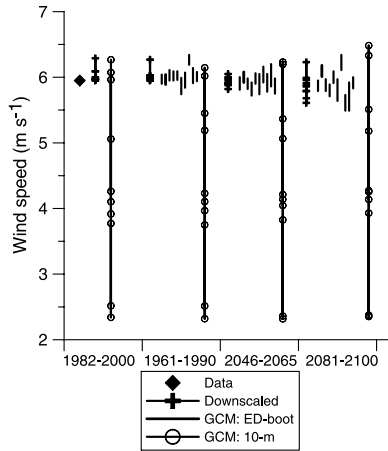


Figure 2. The observed mean wind speed from Copenhagen for 1982–2000, along with grid-cell average mean wind speeds for the grid-cell containing Copenhagen from the ten GCMs (GCM: 10-m) for four time periods (1982–2000, 1961–2000, 2046–2065 and 2081–2100). Also shown is the range of empirically downscaled wind speeds for Copenhagen from the ten GCMs (Downscaled) and the range of the 100 bootstrapped downsampling results from each of the ten GCMs (GCM: ED-boot). The points shown for the downscaled and GCM realizations indicate the results from individual GCMs, and the bootstrap resampling results are shown in the following order by GCM: MRI, ECHAM, GFDL, IPSL, CCCMA, GISS, BCCR, BCC, CNRM, MIROC.

output from each GCM. The models were tested to evaluate that each of the predictors substantially contributes to variance explanation. For example, for the Copenhagen station the Weibull A regression coefficients are 371.27, 0.21609 and 0.81198. For 1982–2000, the observed value of A is 6.69. The predictors are 0.01393, -0.51527 , and 2.0688 and thus each contributes to the downscaled value of 6.74.

[9] The resulting models can then be applied to estimates of \overline{PG} , $\bar{\zeta}$, and $\sigma(\zeta)$ from GCM output for any time period to derive Weibull A and k parameters for each station from which the mean wind speed (\bar{U}) is computed from:

$$\bar{U} = A\Gamma\left(1 + \frac{1}{k}\right)$$

where Γ is the gamma function.

[10] Percentiles ($X \times 100$) of the wind speed distribution are computed from:

$$U_x = A(-1 \cdot \ln(1 - X))^{1/k}$$

Energy density is given by:

$$E = \frac{1}{2} \rho A^3 \Gamma\left(1 + \frac{3}{k}\right)$$

where ρ is air density.

[11] The empirical downscaling approach described above was applied to output from ten GCMs to develop

projections of wind speed probability distributions at 45 surface stations for 1961–2000, 2046–2065 and 2081–2100. We apply bootstrap resampling of the time series of predictors from each GCM to assess whether stochastic effects in the GCM simulation of these predictors substantially bias the downscaled Weibull parameters at each site. We further apply the same downscaling technique to multiple GCMs to quantify the range of projections due to differences in model formulation and hence plausible changes in wind climates assuming that the A2 emission scenario [Nakicenovic and Swart, 2000] used here is a realistic projection of climate forcing.

4. Results

[12] Empirically downscaled 10-m wind speeds show greater consistency (both between the GCMs used in the downscaling and with the observations) than the direct GCM output (compare Figure 1 with Figures 3a–3c). For example, the mean observed 10-m wind speed at Copenhagen during 1982–2000 was 6 m s^{-1} , while GCM derived grid-cell average wind speeds vary between 2.3 and 6.3 m s^{-1} for this location, but are between 5.9 and 6.3 m s^{-1} when empirically downscaled from the ten GCMs. At all but one station the downscaled mean wind speed is within $\pm 5\%$ of the independent observations, and the 90th percentile wind speed is within $\pm 2.5\%$ of the observed value. The downscaled values also accurately depict the spatial variability of wind speeds. The correlation between observed mean and 90th percentile wind speeds across the 45 sites for the entire period 1982–2000 and downscaled values from all ten GCMs exceeds 0.99. In considering these performance statistics recall that each application of the downscaling to each individual site and each GCM is completely independent and that the mean and 90th percentile wind speeds are not direct products of the downscaling algorithms. The predictive accuracy of the Weibull parameters generally exceeds that for these derived variables. The energy density (power in the wind) is an aggregate of the entire probability distribution of wind speeds and hence is more difficult to model, at all sites bar 1 the downscaled value is within $\pm 20\%$ of that calculated from observations. Mean wind speeds derived by empirical downscaling from the ten GCMs during each simulation period exhibit greater variability than is manifest in bootstrapping of the output from any individual GCM, indicating the uncertainty in the downscaling is not due to stochastic effects in any individual model but rather differences between the GCMs (Figure 2).

[13] The change of mean wind speed and 90th percentile wind speed between 1961–1990 and the two projection periods (2046–2065 and 2081–2100) from downscaling of the ten GCMs is relatively consistent. The range of percent changes in the mean and 90th percentile wind speed is $\leq 20\%$ for 2046–2065 (Figures 3c and 3d) and $\leq 35\%$ during 2081–2100 (Figures 3f and 3g) at all stations, and is thus comparable to those computed from the GCM grid-cell average mean wind speeds (Figures 1c and 1d). Using the 90th percentile as an index of wind extremes (as in the 3rd Assessment Report of the IPCC [Houghton et al., 2001]), these results would tend to imply 2046–2065 and 2081–2100 will not differ substantially from 1961–1990 in terms of extreme wind speeds. As with the changes in

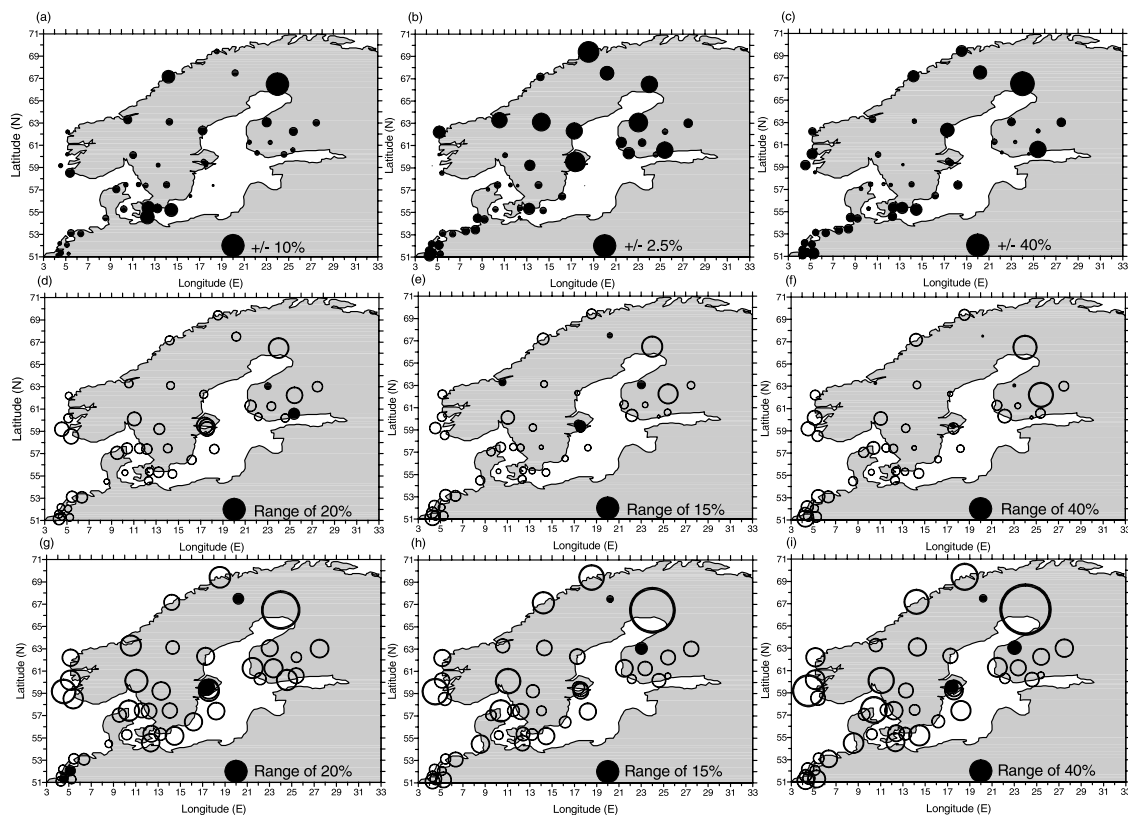


Figure 3. (a–c) Range of downscaled mean and 90th percentile wind speed and energy density from all GCMs relative to independent observations during 1982–2000. A value of $\pm 10\%$ means downscaled mean wind speeds from all ten GCM lie within $\pm 10\%$ of the observed values. (d–i) Consistency in the change of downscaled mean wind speed (Figures 3d and 3g), downscaled 90th percentile wind speed (Figures 3e and 3h), and energy density at each station from the ten GCMs for the future periods relative to 1961–1990 (Figures 3f and 3i). Figures 3d–3f show results for 2046–2065 (i.e., $((2046–2065) - (1961–1990))/(2046–2065)$). Figures 3g–3i show the same information for 2081–2100 relative to 1961–1990. If all the downscaled values indicated declines in the specified parameter the symbol is solid, if the results from the downscaling of different GCMs span zero the symbol is an open circle. No stations exhibited consistent increases in downscaled values from each of the ten GCMs. The diameter of the symbol used in each frame is linearly related to the data range.

downscaled mean and 90th percentile wind speed, the results for energy density at each of the stations tend to span zero with downscaled results from some GCMs showing increases and others decreases. It is asserted, therefore, that there is not a consistent signal with regards to an increase or decrease of the mean and 90th percentile wind speed or energy density in either climate projection period relative to 1961–1990. However, it may be notable that at no site did downscaling values from all GCMs for the future period exceed those computed for 1961–1990 for the mean or 90th percentile wind speed or the energy density. Also, downscaling results from different GCM exhibit increased diversity at the end of C21st. The former implies wind speeds are unlikely to increase relative to the end of the C20th, while the latter indicates reduced confidence in the projections for the end of C21st relative to the middle of this century.

5. Summary

[14] The downscaled mean and 90th percentile wind speed over northern Europe during the C21st are likely to differ from those that prevailed during the end of the C20th by less than approx. $\pm 15\%$. This climate change signal is

currently comparable to the variation in downscaling results due to variation in GCM simulation of the downscaling predictors. While these changes are of relatively small magnitude and there is no evidence for significant evolution of the energy density either, it should be noted that the uncertainty in energy density projections is larger than for the other two parameters. Thus although this work suggests wind energy will continue to be a stable resource for electricity generation in northern Europe over the next sixty years, further work is required to narrow these uncertainty bounds to facilitate integration in impact research and strategic planning for the energy sector.

[15] **Acknowledgments.** The GCM data used are taken from data portal developed for the 4th Assessment Report of the Intergovernmental Panel on Climate Change. We gratefully acknowledge the international modelling groups for providing their data, the Program for Climate Model Diagnosis and Intercomparison for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling and their Coupled Model Intercomparison Project and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy. Limited financial support was provided by 'Impacts of Climate Change on Renewable Energy Sources and their Role in the Energy System: 2003–2006' funded by the Nordic Energy Research and grants to Indiana

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